Boundary Project: Geochemistry of Volcanic Rocks of the Wallace Formation, Beaverdell Area, South-Central British Columbia (NTS 082E/06E, 07W, 10W, 11W)

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KEYWORDS: Quesnellia, Triassic, Wallace Formation, Beaverdell, calcalkaline

INTRODUCTION

The Boundary Project was initiated in 2005 with the purpose of better characterizing the lithological and geochemical variations within and between the various Paleozoic sequences in the southern Okanagan region along the American border (Massey 2006, 2007; Massey and Duffy 2008a). Pre-Jurassic rocks in the Beaverdell area were assigned by Reinecke (1915) to the 'Wallace Group' (single quotation marks are used to highlight the actual term used in the paper) and correlated, in part, with Paleozoic sequences to the south, including the Anarchist schist and the Attwood 'series'. Little (1957, 1961) and Tempelman-Kluit (1989a, b) extended this work to the east and west including these rocks in the 'Anarchist Group'.

The pre-Jurassic rocks of the Beaverdell area (Figure 1), however, differ significantly from the type Anarchist schist to the south (Massey and Duffy, 2008a). They are dominated by fine- to medium-grained clastic sedimentary rocks that are essentially unmetamorphosed, though they do show extensive hornfelsing from Jurassic plutons. Limestone and greenstone members occur in the Crouse Creek area, and are stratigraphically the lowest exposed units. Significantly, there is no chert developed in the sequence. No penetrative deformation was observed, except for one small area, to the west of Crouse Creek.

Massey and Duffy (2008a) proposed to revert to Reinecke's original terminology of 'Wallace' for these rocks, though at the formation level rather than the group level. It should be noted, however, that not all of the area originally mapped as Wallace by Reinecke (1915) is actually underlain by pre-Jurassic rocks—there is a significant amount of younger intrusive material. In particular, many rocks mapped as so-called pyroxene-phyric volcanic rocks in Reinecke's Wallace are actually porphyry dikes of Tertiary age, and in one area, east of Collier Lake, pyroxene-phyric flows of the Eocene Marron Formation.

No geochronological or paleontological data are currently available for the Wallace Formation rocks and correlation is therefore difficult. As stated above, it is lithologically dissimilar to any of the Paleozoic sequences to the south. It does, however, show some similarities to parts of the Middle–Late Triassic Brooklyn Formation of the Greenwood area (Fyles, 1990) or the Franklin Camp, though lacking the distinctive basal sharpstone conglomerate, possibly due to a lack of exposure. The Wallace Formation is intruded by the West Kettle batholith, now known to be of Late Triassic age (Massey et al, 2010).

WALLACE FORMATION

The lowest exposed unit in the Wallace Formation is the Larse Creek limestone member. Contact with the overlying greenstone member is not exposed, but the limestone is estimated to be at least 100 m thick. It is grey on weathered surfaces, varying from black to grey to white on fresh surfaces. It is massive to well bedded and laminated. Thin siliceous and minor calcsilicate veins weather with positive relief. Macrofossils are absent and conodonts have not been recovered to date.

The Crouse Creek greenstone member overlies the limestone member. This unit comprises mostly massive mafic flows, though amygdules are not uncommon. The flows are medium to dark green-grey, bluish green or black in colour. They may show bright green epidosite patches up to 30 cm across (Figure 2a) and veins of quartz–chlorite±epidote±calcite. Many flows are fine-grained and aphyric, but feldspar-phyric and pyroxene-feldspar–phyric flows are also common. Phenocrysts are 1–2 mm in size. Volcanic breccia, lapilli tuff, pyroxene lapilli tuff or chloritic metatuff (Figures 2b–d) and minor laminated limestone are found interbedded in the flows. Some volcanic breccias also contain limestone and clastic sediment clasts.

Most of the exposed Wallace Formation is typically interbedded and laminated siltstone and argillite. Siltstone beds are light buff to pale grey in colour, whereas the argillite is dark grey. Weathered surfaces may be broken with a coating of rusty oxides. Individual beds can range up to 3 cm thick with laminations of ~1–2 mm. The sedimentary rocks are often siliceous or porcelaneous and may be recrystallized due to hornfels development by Triassic and Jurassic intrusions. Occasional white, tan or grey limestone interbeds vary from several centimetres up to five metres thick. The limestone is massive and may be recrystallized due to the development of hornfels or variable silicification and skarn.

Coarser clastic beds are also found, though less common than the siltstone-argillite interbeds. Sandstone beds are grey, medium to coarse grained, and generally massive. Hornfelsed sandstone is recrystallized to feldspar-quartz-amphibole assemblages that can be difficult to discriminate from microdiorite or microgranodiorite in the field. Con-

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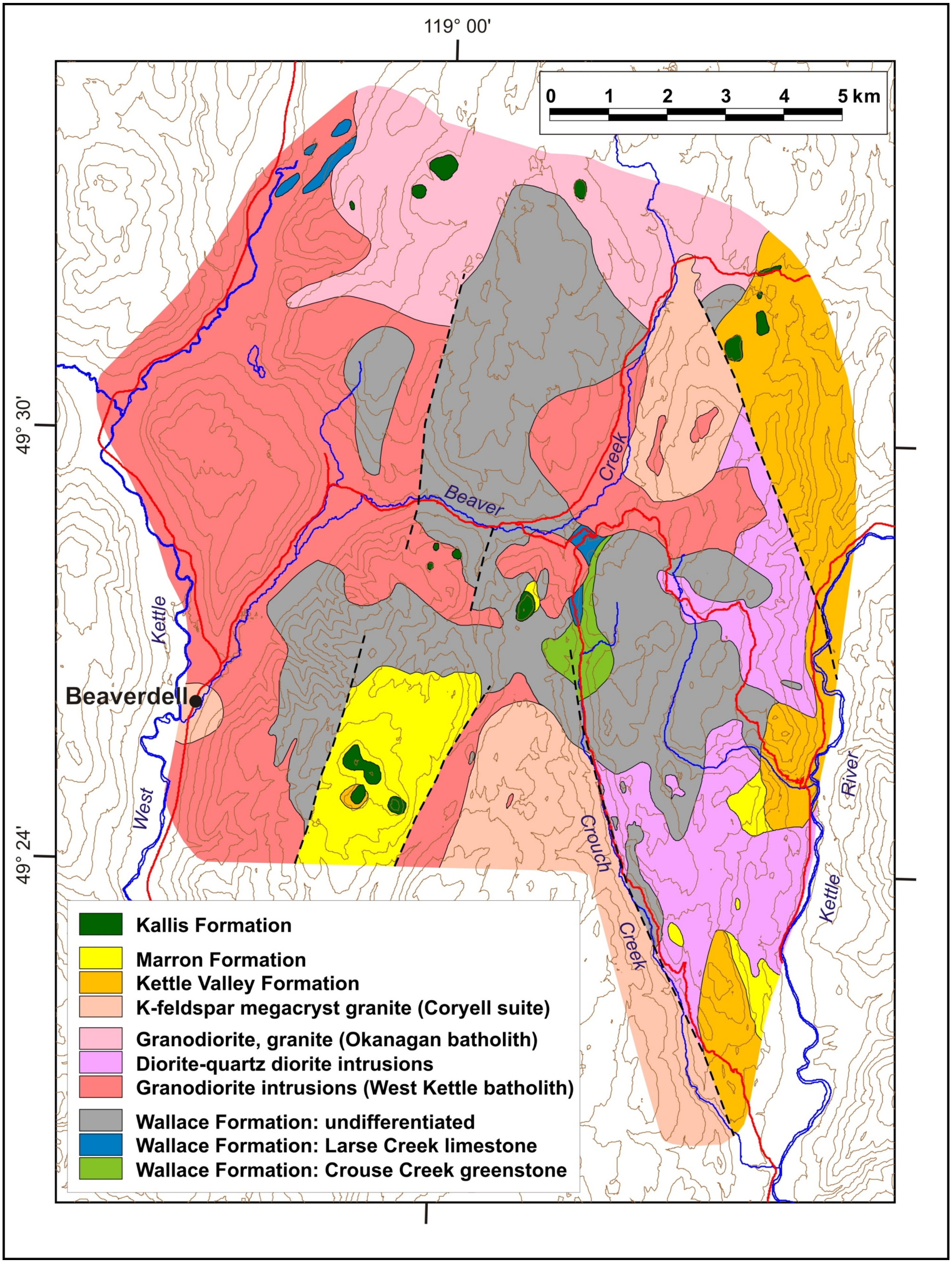

Figure 1. Geology of the area east of Beaverdell, south-central British Columbia (after Massey and Duffy, 2008b). The extent of coloured polygons shows the limit of the area mapped in 2007.

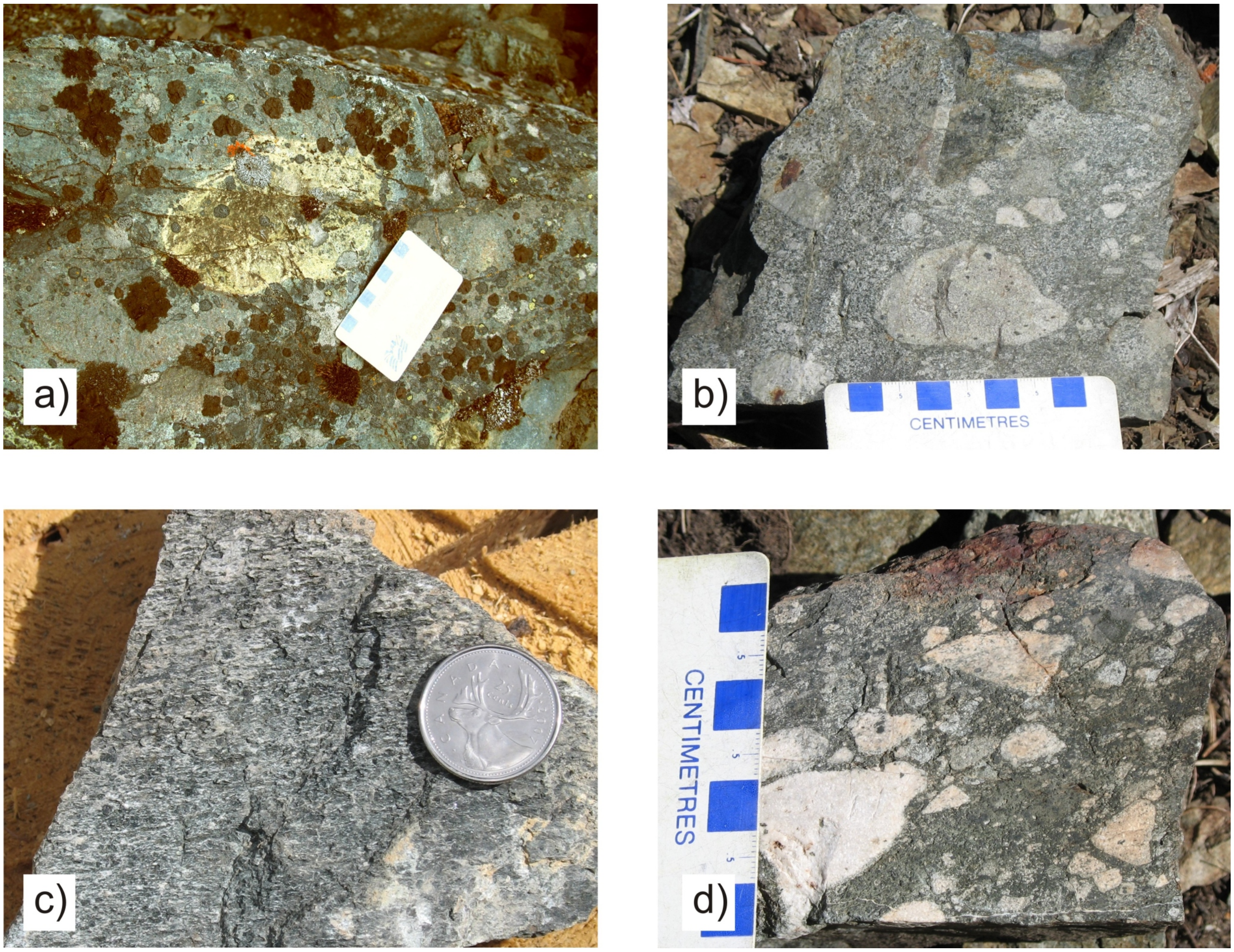

Figure 2. The Crouse Creek greenstone member of the Wallace Formation, south-central British Columbia: **a)** epidosite patch in massive greenstone (07NMA31-01; UTM Zone 11, 5479991N, 358567E, NAD83); **b)** pyroxene crystal-lapilli tuff (07NMA32-04; UTM Zone 11, 5479062N, 358777E, NAD83); **c)** pyroxene-feldspar crystal tuff (07NMA33-02; UTM Zone 11, 5479283N, 357806E, NAD83); **d)** pyroxene crystal-lapilli tuff with rhyolite clasts (07NMA32-04; UTM Zone 11, 5479062N, 358777E, NAD83).

glomerate and pebbly sandstone have matrix-supported, rounded to subangular clasts. The clasts are dominantly of siliceous siltstone and argillite, but also can include limestone. The latter are usually larger in size. All clasts appear to be intraformational and no exotic rock types have been observed.

Fine-grained basalt is found within the sedimentary section, particularly in the area north of Canyon Creek. The basalt is aphyric, dark to medium grey in colour, weathering light grey to buff with a greenish tinge. Outcrops are massive with blocky jointing and fractures. Direct contacts were not observed, and it is unclear if the basalt forms interbedded flows or dikes.

GEOCHEMISTRY OF THE VOLCANIC ROCKS

Fourteen samples of the Crouse Creek greenstone member and six basalt samples from the clastic sediment package were analyzed for whole-rock major, minor and trace elements. Results are summarized in Table 1. Samples range in composition from basalt to andesite and dacite (Figure 3). They show some mobility of alkali elements but generally all preserve a subalkalic, calcalkaline character (Figures 3, 4). Minor- and trace-element diagrams further confirm the formation of both suites in an arc environment, though not all diagrams successfully discriminate between calcalkaline and island-arc tholeiite basalt (Figures 5–8). A continental arc environment is suggested by both major- and trace-element data (Figures 9, 10). Extended trace-element plots show typical calcalkaline patterns with the negative Nb-Ta anomaly characteristic of volcanic arcs (Figure 11).

REGIONAL CORRELATIONS

The calcalkaline, volcanic arc character of the Wallace Formation volcanic rocks is comparable to that of the Triassic Brooklyn Formation (Dostal et al., 2001), but differs distinctly from that of the tholeiitic Paleozoic Knob Hill Complex (Massey, 2008) and Anarchist schist (Massey, un-

Table 1. Whole-rock chemical analyses for Wallace Formation volcanic rocks, south-central British Columbia. Major elements and Rb, Sr, Ba, Y, Zr, Nb, V, Ni and Cr determined by x-ray fluorescence (XRF; major elements on fused disc, trace elements on pressed-powder pellet) by Teck (Global Discovery) Labs (Vancouver). Rare earth elements (REE), Th, Ta and Hf determined by peroxide fusion–ICP-MS by Memorial University of Newfoundland (St. John's). Dashes indicate element determinations below detection limit; blank values indicate element not analyzed.

	Crouse Creek Member										
Analytical parameter	**07NMA22-13**	**07NMA26-05A**	**07NMA26-05B**	**07NMA31-01a**	**07NMA31-01b**	**07NMA31-04**	**07NMA31-08**	**07NMA31-12**	**07NMA32-01**	**07NMA33-03**	**07NMA33-04**
SiO_2	52.68	52.26	52.54	52.56	52.86	61.37	55.12	59.37	47.16	50.42	53.30
TiO_2	0.62	0.64	0.75	0.69	0.61	0.61	0.88	0.50	0.60	0.54	0.62
Al_2O_3	12.02	19.82	18.91	17.72	11.96	14.93	16.10	16.17	17.57	15.72	17.60
Fe_2O_3t	9.13	8.02	8.52	9.77	9.14	4.54	8.82	7.01	8.48	9.48	8.61
MnO	0.18	0.22	0.25	0.17	0.18	0.07	0.11	0.10	0.15	0.20	0.14
MgO	10.13	3.34	3.35	4.79	10.13	2.94	5.94	3.62	6.98	6.77	5.50
CaO	10.04	7.52	7.96	8.44	9.90	2.87	6.93	8.42	9.80	12.22	8.53
Na_2O	1.80	4.98	4.77	2.42	1.84	3.21	2.70	3.56	2.35	1.99	2.54
K_2O	1.42	1.40	0.92	1.04	1.35	3.81	0.69	0.37	0.82	0.53	1.27
P_2O_5	0.33	0.20	0.24	0.20	0.33	0.29	0.17	0.15	0.18	0.16	0.17
BaO	0.07	0.08	0.02	0.07	0.08	0.20	0.07	0.03	0.08	0.05	0.09
LOI	1.43	1.34	1.43	2.12	1.61	4.89	2.44	0.44	5.43	1.38	1.56
Total	99.85	99.78	99.66	99.99	99.99	99.73	99.97	99.74	99.60	99.46	99.93
Rb	28	49	16	21	27	86	11		20	7	27
Sr	367	708	423	372	359	739	290	391	452	390	430
Ba	741	748	233	740	764	1993	684	326	782	451	877
Y	14	15	20	16	14	15	16	12	10	14	13
Zr	70	60	64	51	68	207	92	55	51	52	55
Nb	8	6	8	6	8	23	12	6	8	8	8
V	204	206	224	279	210	98	201	173	235	229	253
Co	42	22	32	33	41	20	39	38	31	38	36
Ni	15	-	-	8	13	13	8	74	102	117	45
Cr	749	17	11	33	777	48	65	248	367	404	151
La		6.383	7.440	6.794	12.131	51.696		6.691	5.850		
Ce		13.237	16.291	14.909	24.345	94.025		14.425	12.855		
Pr		2.004	2.431	2.037	3.204	10.459		1.939	1.697		
Nd		10.630	12.562	9.522	13.896	38.931		9.093	7.934		
Sm		3.020	3.658	2.614	3.081	6.097		2.048	2.010		
Eu		1.113	1.326	0.769	0.963	1.354		0.756	0.674		
Gd		3.663	4.782	2.937	3.198	4.476		2.329	2.312		
Tb		0.582	0.713	0.471	0.484	0.576		0.392	0.380		
Dy		3.833	4.597	3.131	3.037	3.220		2.484	2.436		
Ho		0.827	1.072	0.668	0.621	0.598		0.523	0.505		
Er		2.596	3.187	1.992	1.821	1.642		1.566	1.571		
Tm		0.366	0.449	0.292	0.259	0.224		0.219	0.219		
Yb		2.389	3.135	2.008	1.681	1.405		1.593	1.444		
Lu		0.365	0.467	0.322	0.260	0.231		0.230	0.223		
Hf		2.098	2.645	1.574	2.124	6.191		1.520	1.318		
Ta		0.168	0.151	0.158	0.280	0.932		0.143	0.148		
Th		0.901	0.990	1.214	2.391	11.435		1.358	1.010		
Latitude	49.456604	49.444199	49.444479	49.456109	49.456109	49.454224	49.450260	49.442010	49.440026	49.448959	49.448996
Longitude	-118.950777	-118.910477	-118.910440	-118.951612	-118.951612	-118.950781	-118.950608	-118.949914	-118.949570	-118.960509	-118.959758
UTM Zone	11	11	11	11	11	11	11	11	11	11	11
Northing	5480045	5478591	5478622	5479991	5479991	5479780	5479339	5478421	5478200	5479213	5479216
Easting	358629	361515	361518	358567	358567	358622	358623	358650	358669	357902	357957

Table 1. (continued)

	Crouse Creek Member					Aphyric basalt (?) dikes					
Analytical parameter	07NMA33-05E2	07NMA35-03	07NMA35-05	07NMA35-06	07NMA35-08	07NMA18-14	07NMA28-08	07NMA29-08	07NMA29-13	07NMA29-14	07NMA29-17A
SiO_2	61.48	56.03	59.04	55.14	53.04	55.79	57.43	51.41	51.53	51.13	50.45
TiO_2	0.46	0.62	0.52	0.65	0.75	0.81	0.52	0.77	0.68	0.72	0.72
Al_2O_3	17.76	17.69	18.01	17.81	17.56	16.19	18.04	16.84	19.24	18.46	18.56
Fe_2O_3t	5.87	7.97	5.66	8.46	8.44	9.46	6.30	8.98	8.08	9.98	8.94
MnO	0.10	0.18	0.14	0.21	0.19	0.09	0.11	0.20	0.18	0.19	0.24
MgO	1.92	3.87	1.86	3.84	3.47	5.06	3.06	5.00	3.25	4.09	3.40
CaO	6.06	6.82	5.29	7.71	7.17	7.42	6.19	8.71	7.86	6.72	9.83
Na_2O	3.82	3.99	4.81	3.69	2.75	2.95	4.06	3.80	4.82	4.43	3.05
K_2O	0.79	0.77	1.70	0.83	1.32	0.49	2.77	1.34	0.93	1.47	0.90
P_2O_5	0.20	0.27	0.27	0.27	0.28	0.12	0.34	0.34	0.23	0.29	0.23
BaO	0.08	0.06	0.13	0.05	0.13	0.02	0.16	0.08	0.04	0.10	0.07
LOI	1.31	1.71	2.30	1.04	4.56	1.58	0.80	2.17	2.61	2.15	3.15
Total	99.85	99.98	99.73	99.70	99.66	99.98	99.78	99.64	99.45	99.73	99.54
Rb	17	24	54	20	35	12	53	23	19	32	18
Sr	459	632	462	496	597	279	722	687	729	680	566
Ba	814	553	1299	549	1346	193	1645	781	439	995	743
Y	13	14	14	16	16	18	16	17	19	16	17
Zr	82	86	97	80	81	75	87	57	71	58	61
Nb	9	10	11	10	10	8	7	7	4	8	8
V	112	178	110	199	230	222	194	293	205	276	231
Co	26	27	20	28	26	36	25	26	21	24	23
Ni	-	-	-	-	-	17	6	15	4	6	4
Cr	24	26	19	19	18	76	24	44	16	28	33
La					12.8245	7.965				7.665	
Ce					26.457	16.712				15.885	
Pr					3.6315	2.277				2.206	
Nd					17.285	10.986				11.444	
Sm					3.9535	2.820				3.187	
Eu					1.161	1.042				1.074	
Gd					3.963	3.986				4.103	
Tb					0.616	0.594				0.604	
Dy					3.629	3.847				3.878	
Ho					0.895	0.873				0.867	
Er					2.6485	2.650				2.621	
Tm					0.3695	0.393				0.352	
Yb					2.3945	2.541				2.543	
Lu					0.337	0.375				0.389	
Hf					2.071	2.732				2.099	
Ta					0.3175	0.403				0.136	
Th					1.8165	1.381				1.109	
Latitude	49.449362	49.393454	49.390055	49.388879	49.386997	49.479276	49.460473	49.437396	49.437550	49.437930	49.438132
Longitude	-118.958177	-118.924602	-118.922569	-118.921878	-118.920446	-119.010463	-118.932273	-118.898797	-118.894089	-118.894896	-118.887550
UTM Zone	11	11	11	11	11	11	11	11	11	11	11
Northing	5479254	5472976	5472594	5472462	5472251	5482679	5480440	5477813	5477822	5477866	5477875
Easting	358072	360347	360485	360532	360630	354371	359981	362342	362684	362627	363160

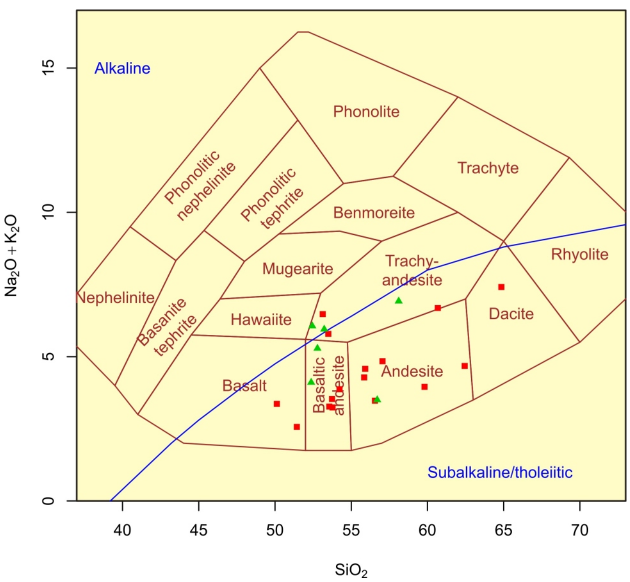

Figure 3. Total alkali elements versus SiO_2 (anhydrous weight percent) plot for Wallace Formation volcanic rocks, south-central British Columbia. Classification fields and nomenclature after Cox et al. (1979). The alkaline-subalkaline dividing line after Irvine and Baragar (1971). The Crouse Creek greenstone member is indicated by red squares; the aphyric basalt (dikes?) in clastic sedimentary rocks is indicated by green triangles.

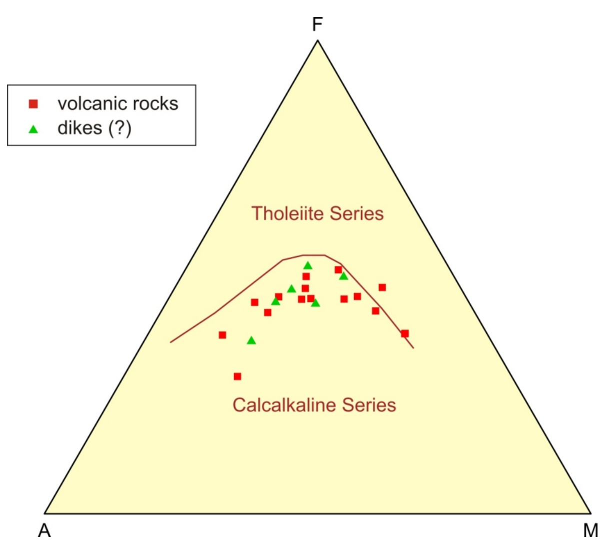

Figure 4. AFM diagram for Wallace Formation volcanic rocks, south-central British Columbia, after Irvine and Baragar (1971); A = Na_2O + K_2O; F = FeO_{total}; M = MgO, all as anhydrous weight percents. Symbols are as in Figure 3.

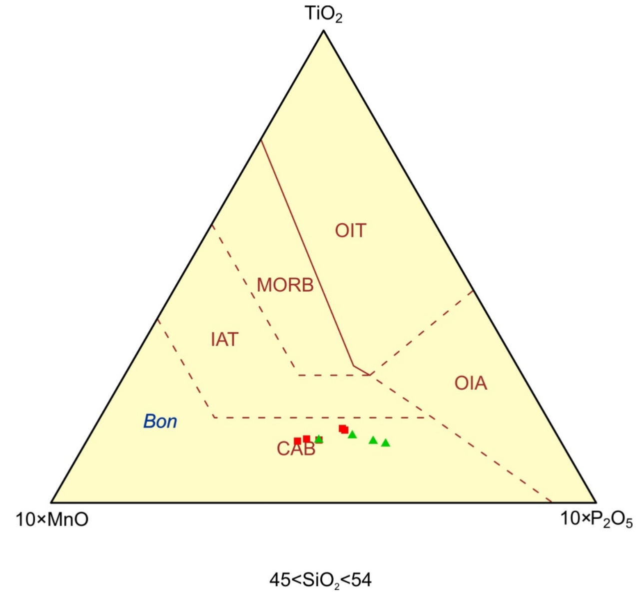

Figure 5. MnO-TiO_2-P_2O_5 (anhydrous weight percent) discrimination diagram for Wallace Formation volcanic rocks, south-central British Columbia, after Mullen (1983). Abbreviations: Bon, boninite; CAB, calcalkaline basalt; IAT, island-arc tholeiite; MORB, mid-ocean-ridge basalt; OIA, ocean-island alkali basalt; OIT, ocean-island tholeiite. Symbols are as in Figure 3. Only basaltic samples with 12<CaO+MgO<20 wt. % are shown.

published data, 2006–2009). Further, the Late Triassic West Kettle batholith, which intrudes the Wallace Formation, has a similar calcalkaline, volcanic arc character and identical normalized REE patterns to Wallace Formation volcanic rocks (Massey et al, 2010). This suggests that the West Kettle batholith may, at least in part, be coeval with the Wallace Formation.

The correlation of the basalt dikes (?) found within the clastic sedimentary rocks of the Wallace Formation is still uncertain. They are indistinguishable from the Crouse Creek greenstone member in nearly all geochemical diagrams and are most likely contemporaneous and consanguineous. However, if indeed they are intrusive, they may be younger in age. Comparison with Middle Jurassic diorite of the area shows the latter, though similarly calcalkaline (Massey et al., 2010), has steeper REE (Figure 12) and extended trace-element patterns (Figure 11c), which suggests they are not consanguineous. Similar comparisons can be made with the Early Jurassic Elise Formation (Höy and Dunne, 1997). Correlation with volcanic rocks of the nearby Tertiary Penticton Group is also unlikely as the latter are alkalic in character.

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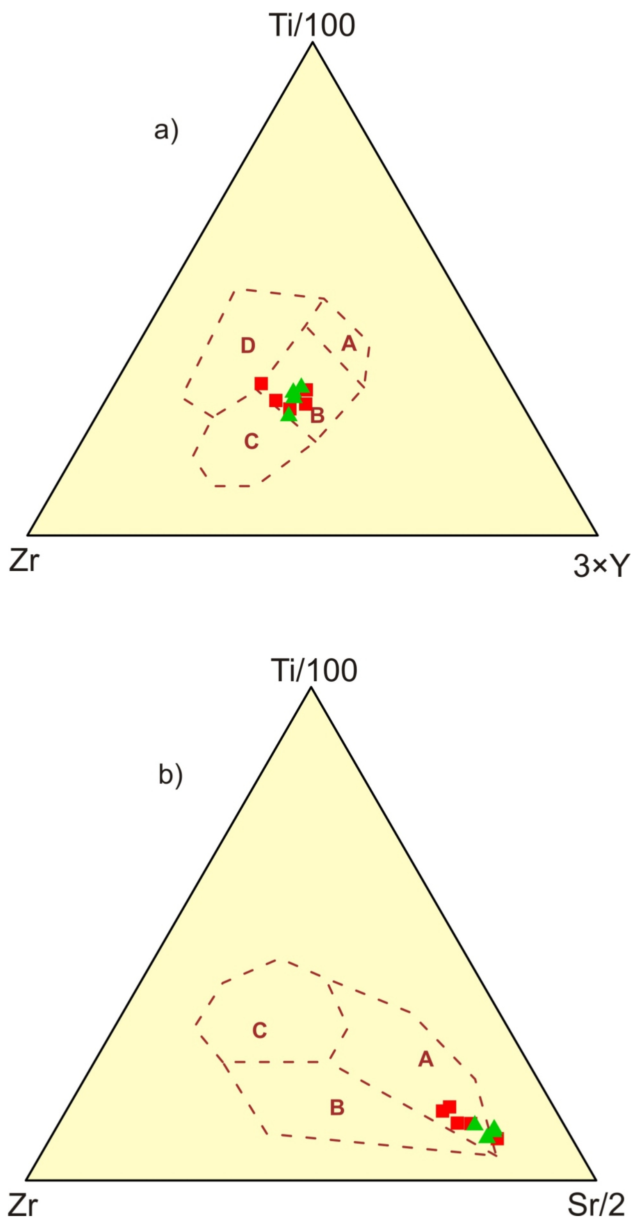

Figure 6. Trace-element discrimination diagrams for Wallace Formation volcanic rocks, south-central British Columbia, after Pearce and Cann (1973). Symbols are as in Figure 3. Only basaltic samples with 12<CaO+MgO<20 wt. % are shown: **a)** Ti-Zr-Y diagram; A, island-arc tholeiites; B, mid-ocean ridge basalts, island-arc tholeiites and calcalkaline basalts; C, calcalkaline basalts; D, within-plate basalts; **b)** Ti-Zr-Sr diagram; A, island-arc tholeiites; B, calcalkaline basalts; C, mid-ocean-ridge basalts.

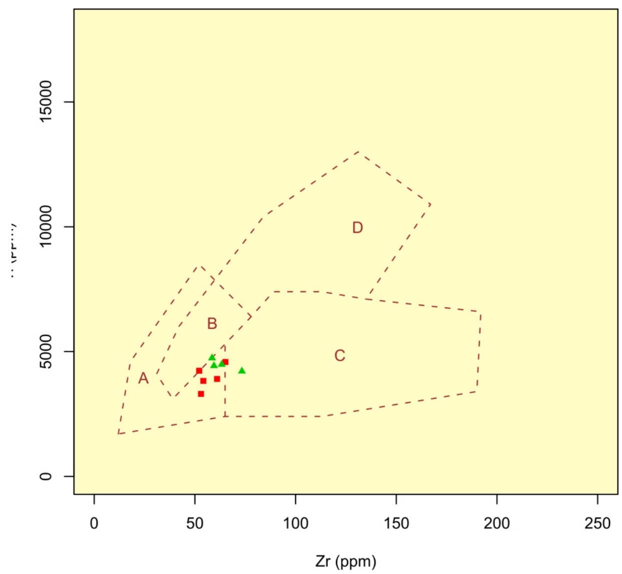

Figure 7. Zr-Ti discrimination diagram for Wallace Formation volcanic rocks, south-central British Columbia, after Pearce and Cann (1973). A, island-arc tholeiites; B, mid-ocean ridge basalts, island-arc tholeiites, calcalkaline basalts; C, calcalkaline basalts; D, within-plate basalts. Symbols are as in Figure 3. Only basaltic samples with 12<CaO+MgO<20 wt. % are shown.

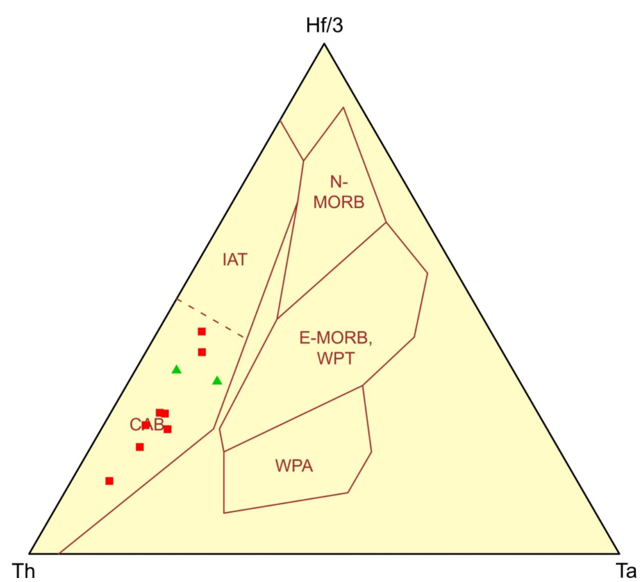

Figure 8. Th-Hf-Ta discrimination diagram for Wallace Formation volcanic rocks, south-central British Columbia, after Wood (1980). Abbreviations: CAB, calcalkaline basalt; E-MORB, enriched mid-ocean-ridge basalts; IAT, island-arc tholeiite; N-MORB, normal mid-ocean ridge basalts; WPA, within-plate alkali basalt; WPT, within-plate tholeiite. Symbols are as in Figure 3. Only basaltic samples with 12<CaO+MgO<20 wt. % are shown.

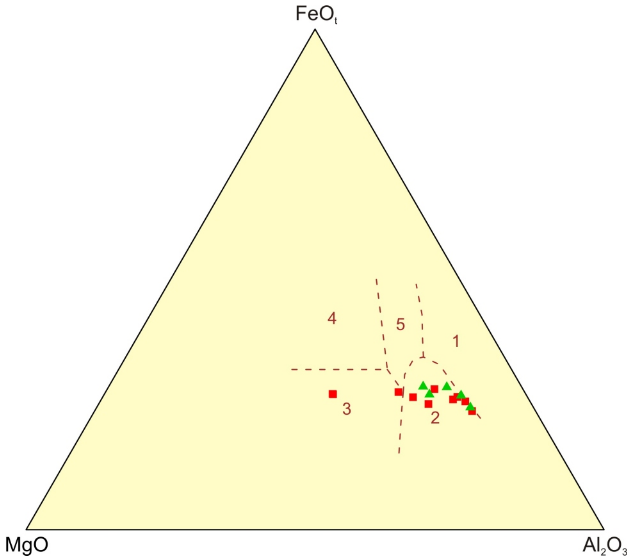

Figure 9. MgO-FeO$_t$-Al$_2$O$_3$ (anhydrous weight percent) discrimination diagram for Wallace Formation volcanic rocks, south-central British Columbia, after Pearce et al. (1977). 1, spreading centre island; 2, island-arc and active continental margin; 3, mid-ocean-ridge basalt; 4, ocean island; 5, continental flood basalts. Symbols are as in Figure 3. Only samples of intermediate composition, 51<SiO_2<56 wt. %, are plotted.

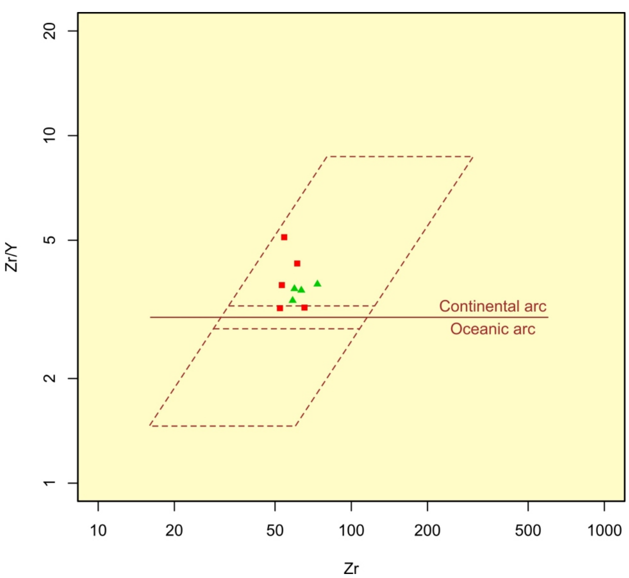

Figure 10. Zr–Zr/Y discrimination diagram Wallace Formation volcanic rocks, south-central British Columbia, after Pearce (1983). Fields of continental (upper) and oceanic-arc (lower) basalts separated on the basis of a Zr/Y value of 3. Field of overlap between the two basalt types indicated. Symbols are as in Figure 3. Only basaltic samples with 12<CaO+MgO<20 wt. % are shown.

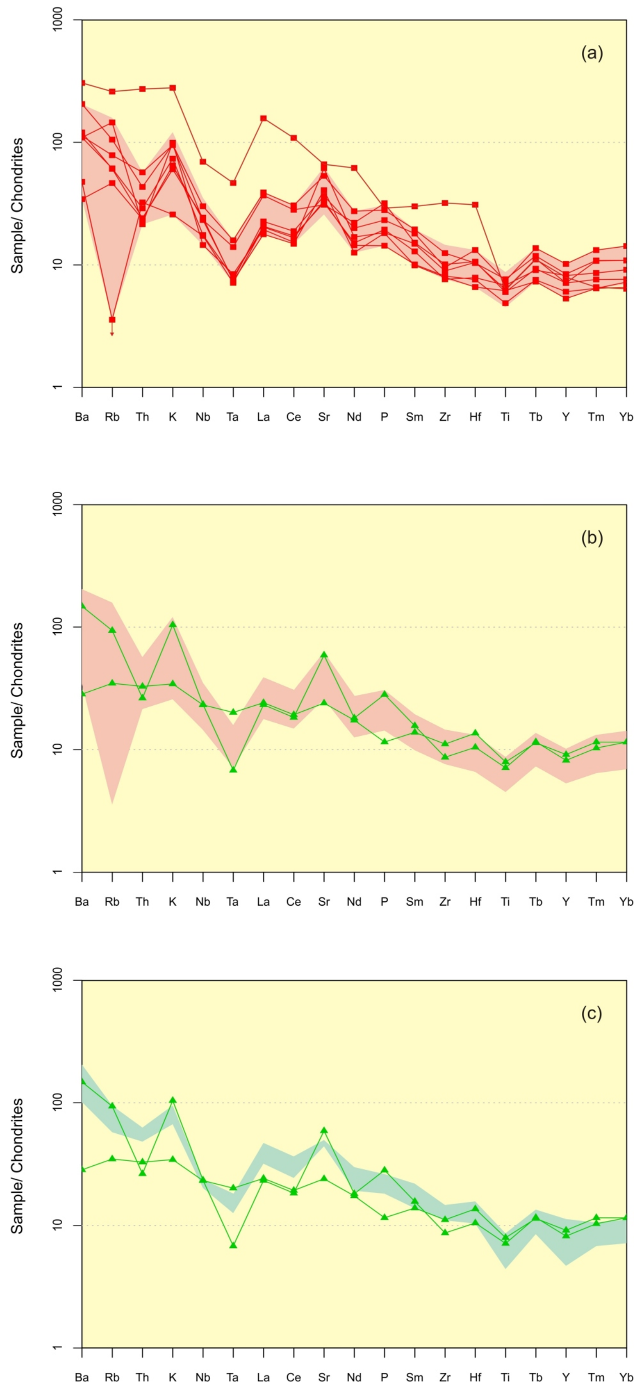

Figure 11. Trace-element concentrations normalized to chondrite, after Thompson (1982), samples from south-central British Columbia: **a)** Crouse Creek member volcanic rocks; only samples with the complete range of determined elements are plotted; the pink shaded field shows the range for all samples except for dacite sample 07NMA31-04; **b)** aphyric basalts (dikes?) in clastic sedimentary rocks; only samples with the complete range of determined elements are plotted; the pink shaded field as in a); **c)** aphyric basalts (dikes?) in clastic sedimentary rocks compared to Jurassic diorite of the Beaverdell area (pale green shaded field; Massey et al., 2010).

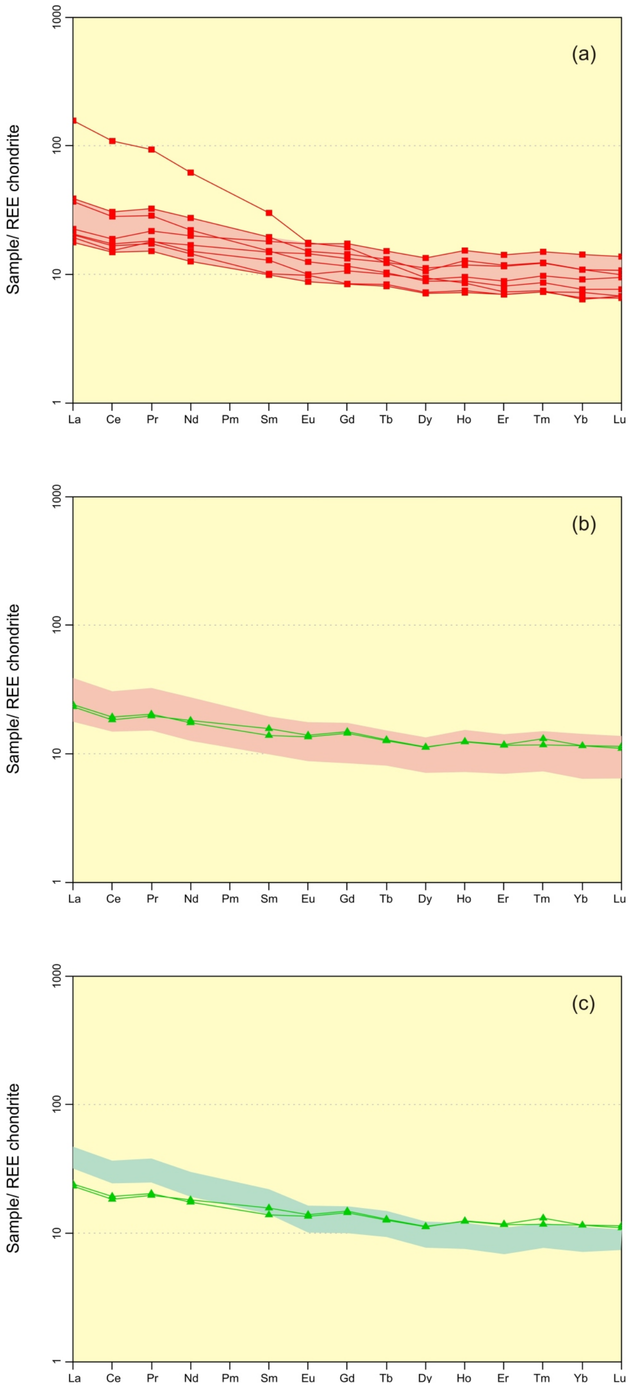

Figure 12. Rare earth element abundances normalized to chondrite (after Nakamura, 1974): **a)** Crouse Creek member volcanic rocks; the pink shaded field shows the range for all samples except for the dacite sample 07NMA31-04; **b)** aphyric basalts (dikes?) in clastic sedimentary rocks; the pink shaded field as in a); **c)** aphyric basalts (dikes?) in clastic sedimentary rocks compared to Jurassic diorite of the Beaverdell area, pale green shaded field (Massey et al., 2010).

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